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# Beryllium Availability—Market Economy Countries

## A Minerals Availability Appraisal

By Audrey A. Soja and Andrew E. Sabin

UNITED STATES DEPARTMENT OF THE INTERIOR

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# PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and on mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| °C | degree Celsius | μg/L | microgram per liter |
| cm | centimeter | μg/m³ | microgram per cubic meter |
| ft | foot | Mmt | million metric tons |
| g | gram | mt | metric ton |
| kg | kilogram | mt/yr | metric ton per year |
| km | kilometer | pct | percent |
| lb | pound | st | short ton |
| m | meter | stu | short ton unit |
| m³ | cubic meter | yr | year |

# BERYLLIUM AVAILABILITY—MARKET ECONOMY COUNTRIES

## A Minerals Availability Appraisal

By Audrey A. Soja[1] and Andrew E. Sabin[2]


## ABSTRACT

The Bureau of Mines investigated beryllium resources, production methods, and production costs to estimate the quantity of beryllium available for future use. Eight mining districts and 12 deposits are included in the study; lack of data precluded the evaluation of resources from 6 nonproducing and undeveloped deposits. The study revealed that demonstrated beryllium-bearing resources should be sufficient to meet domestic needs and those of other market economy countries (MEC's) well into the 21st century.

Total demonstrated beryllium-bearing in situ resources from MEC's are estimated at 118 million metric tons (Mmt) of ore containing approximately 33,000 mt beryllium metal. Approximately 111 Mmt ore containing 29,000 mt beryllium was included in the cost analysis and availability sections of this study.

Three Brazilian districts currently produce beryl ore, and one domestic company, Brush Wellman Inc., produces bertrandite ore. Brush Wellman Inc. owns and operates the only MEC facility in the Western Hemisphere for extracting beryllium values from beryl and bertrandite and is the beryllium industry's only fully integrated corporation.



[1]Industry economist.
[2]Geologist.
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## INTRODUCTION

Beryllium resources and the beryllium manufacturing industry are of interest to the United States because beryllium is an important constituent of components for the defense, nuclear, and aerospace industries. The purpose of the Bureau of Mines' beryllium availability study is to estimate the total amount of beryllium available from various economic and potentially economic sources and to estimate the price required for producers and potential producers to recover costs of production and obtain a return on investments. This beryllium availability study contributes to the analytical structure used by the Bureau to develop mineral-related policy recommendations.

This report focuses on major ore producers and potential producers in Argentina, Brazil, Canada, and the United States. Other MEC's, including the Republic of South Africa and Rwanda, have not been included because the combined production from these countries as a percentage of the world total is relatively insignificant (approximately 7 pct in 1983). Production data from the U.S.S.R. and China indicate that they produced the most beryl ore among all foreign nations in 1983; however, lack of data on individual deposits or mining regions precludes the inclusion of these and all other centrally planned economy countries (CPEC's) in this study.

The beryllium industry is relatively small, which makes an availability analysis somewhat limited in scope when compared to other major commodities. In the Western Hemisphere, only one mine produces bertrandite and three Brazilian districts produce the majority of beryl; one company extracts beryllium hydroxide [$Be(OH)_2$] from beryl and bertrandite ores, and two companies convert $Be(OH)_2$ to three basic forms of beryllium. The scope of this report is limited; because beryllium extraction and processing costs are proprietary, the analysis of beryllium does not extend beyond the mining and milling stages. Beryl ore availability and production costs are presented in this report.

Several factors affecting present and future availability of beryllium from known deposits are discussed in this report, e.g., number of ore deposits, deposit size and beryllium grade, mining and milling techniques, market prices of the ore and beryllium products, and demand for beryllium products. To some extent, government regulations, both foreign and domestic, and the value of any commodities recovered with beryllium ores can indirectly impact the availability of beryllium.

Deposit data were procured from deposit site visits, interviews with company officials, and publications. Data used in the availability analysis include recoverable resources, grades of recoverable minerals, capital costs, operating costs, transportation costs, taxes, and royalties. Resources were estimated according to criteria adopted by the U.S. Geological Survey and Bureau of Mines (fig. 1) (*1*).[3] The Bureau of Mines supply analysis model (SAM) computer program processed input data and produced financial summaries and annual cash flows for each deposit, using the discounted-cash-flow-rate-of-return (DCFROR) method.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

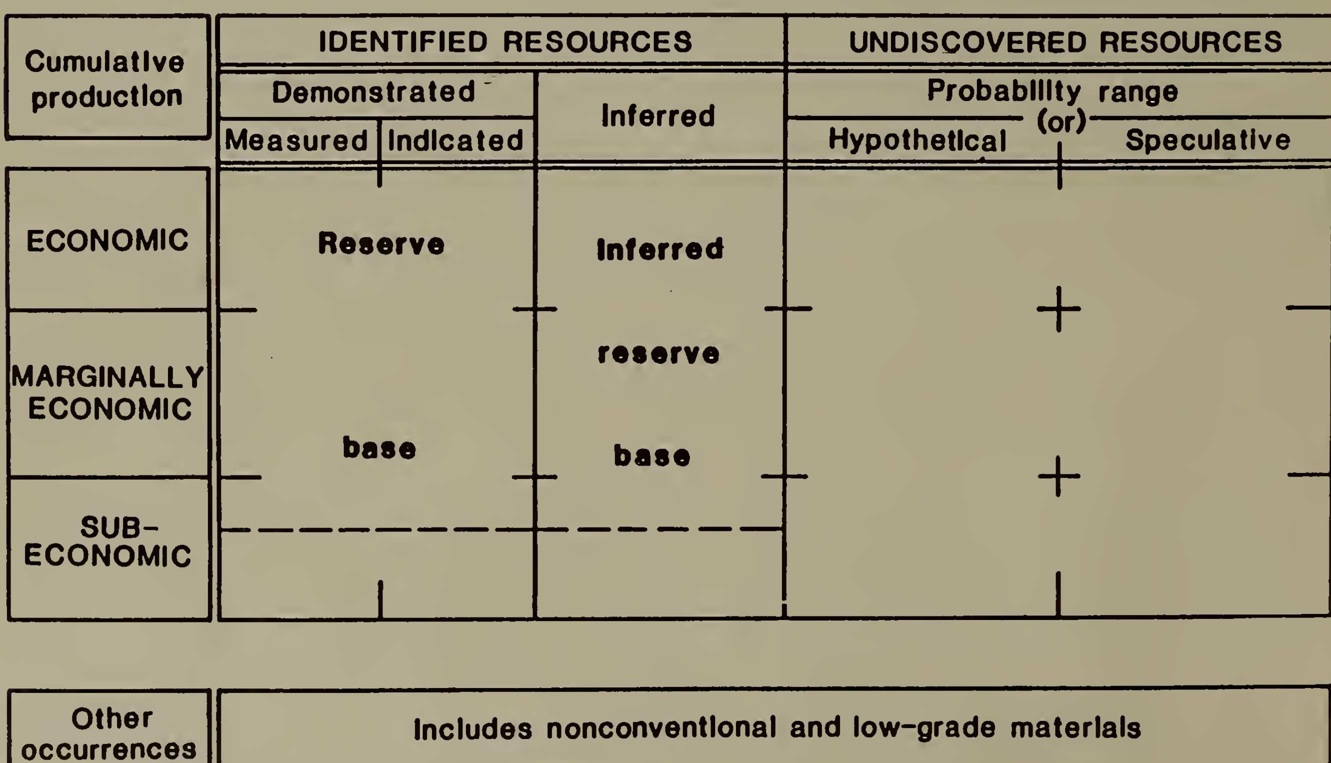


FIGURE 1.—Mineral resource classification categories (*1*).

## ACKNOWLEDGMENTS

Andrew W. Berg, David K. Denton, Jr., and Russell G. Raney, Bureau of Mines Western Field Operations Center, and Robert C. Bowyer and David R. Wilburn of the Minerals Availability Field Office procured data for U.S. mines, deposits, and districts included in this beryllium study.

## BERYLLIUM INDUSTRY

### PRODUCTS AND APPLICATIONS

Beryllium apparently was extracted from beryl as early as 1798, after Vauquelin dissolved beryl in aqueous KOH and precipitated $Be(OH)_2$ by boiling the solution. The metallic form was isolated in 1828, when Wohler and Bussy reduced the chloride with potassium in a platinum crucible. In 1926, beryllium-copper alloys were discovered to have significant mechanical properties. Commercial production of these alloys began in the United States in 1932, while the commercial process for extracting metallic beryllium was not developed until the 1940's (*2*).

Manufactured in three basic forms (alloy, oxide, and metal), beryllium is a very low density metal (two-thirds that of aluminum) that possesses several physical and chemical properties that make it a unique engineering material. Beryllium's negative aspects are toxicity and high costs associated with the extraction process.

Beryllium is generally alloyed with copper. Alloying combines electrical conductivity, thermal conductivity, and high strength with fatigue and corrosion resistance. Beryllium alloys containing nickel, cobalt, aluminum, and/or aluminum-magnesium, as well as copper, are manufactured to meet industrial specifications and needs.

Beryllium is also used in oxide form (beryllia) in ceramics. Beryllia ceramics are useful for their electrical insulating properties and their ability to conduct heat. Beryllia ceramic components are used in computers, electrical insulators, power transistors, and as substrates (foundation sections) for electronic circuitry.

Finally, beryllium can be prepared as a powder, rod, or ingot to be used in its pure metallic state. Beryllium, in both metallurgical powder and ingot form, can be rolled into sheets which can then be fabricated by conventional methods, e.g., deep draw, shear, redraw, shear form, and roll form (*3*). Other qualities of metallic beryllium are its transparency to X-rays, dissipation of heat (*4-5*), and reflection of neutrons. Aerospace vehicle structures, missile and aircraft guidance system components, and other defense-related devices are fabricated from beryllium. Nuclear reactors and nuclear-powered space systems incorporate beryllium components.

Through continuing experimentation, the beryllium industry can tailor beryllium products to industrial requirements. Beryllium mill products are now available in ingot, lump, chip, powder, block, billet, rod, bar, tube, foil, sheet, plate, wire, and other specialty shapes.

### INDUSTRY OVERVIEW

The beryllium industry in the United States, as represented by the vertical configuration in figure 2, comprises four major stages of beryllium production:

1. Ore producers constitute the first stage of the industry. Although a few U.S. producers supply beryl ore in small amounts, Brush Wellman Inc., the only U.S. bertrandite ore producer, and the Brazilian beryl ore producers are the major suppliers of ore from which beryllium is extracted.

2. In the intermediate stage of the industry, $Be(OH)_2$ is extracted from beryl and bertrandite ores. Brush Wellman Inc. operates the only extraction plant currently producing $Be(OH)_2$ in the western world. Cabot Corp., a producer of beryllium products from $Be(OH)_2$, imports most of the beryl ore processed at Brush Wellman's Delta plant in

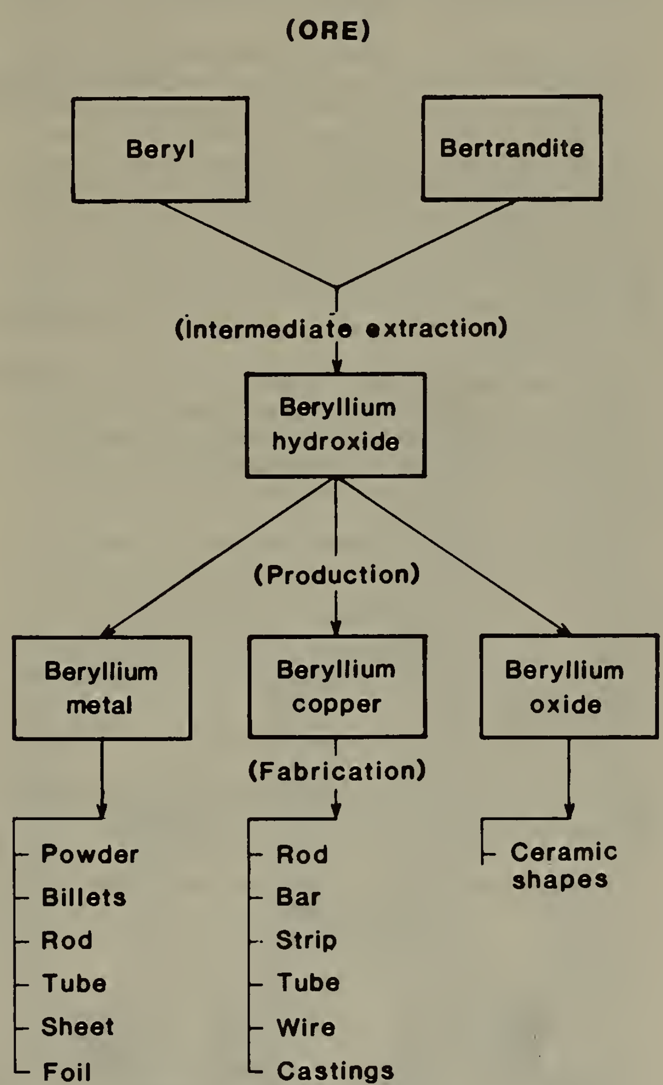


FIGURE 2.—Beryllium industry scheme.

Utah. Brush Wellman converts the beryl ore to $Be(OH)_2$ for Cabot Corp. on a toll basis. All of the bertrandite ore used in the extraction process is mined and milled at Brush Wellman's Spor Mountain deposit in western Utah.

3. In the third stage of the production process, $Be(OH)_2$ is converted into the three major beryllium products for specific industrial requirements, as follows:

a. *Metallic beryllium.*—Through a series of wet chemical steps, $Be(OH)_2$ is converted to $BeF_2$, which in turn is reacted with metallic magnesium to produce metallic beryllium and $MgF_2$.

b. *Beryllium-copper master alloy.*—$Be(OH)_2$ at a low temperature is calcined into an alloy-grade BeO, and charged into an electric arc furnace with carbon and copper. The carbon reduces the BeO to liberate beryllium, which is immediately dissolved in the copper to form a beryllium-copper master alloy containing 4 pct Be.

c. *Beryllium oxide.*—$Be(OH)_2$ is converted into $BeSO_4$, which is calcined in a gas furnace into ceramic-grade BeO.

4. In the fourth stage of production the above materials are then fabricated into commercial forms for sale to a wide range of customers. In the United States, Brush Wellman Inc. and a division of Cabot Corp. have produced metallic beryllium, alloys, and compounds (including BeO), from $Be(OH)_2$ since the 1930's. Historical price trends for these products are illustrated in table 1.

**Table 1.—Historical prices per pound of beryllium powder, oxide, and master alloy (*7*)**

(U.S. dollars per pound)

| Year[1] | Powder[2] | | Oxide[3] | | Be-Cu master alloy[4] | |
|---|---|---|---|---|---|---|
| | Actual | Constant 1984 | Actual | Constant 1984 | Actual | Constant 1984 |
| 1965 .... | 59.00 | 197.06 | 23.00 | 76.82 | 46.00 | 153.64 |
| 1967 .... | 61.00 | 196.42 | 23.00 | 74.06 | 48.00 | 154.56 |
| 1969 .... | 61.00 | 185.44 | 25.00 | 76.00 | 50.00 | 152.00 |
| 1971 .... | 61.00 | 172.63 | 23.00 | 65.09 | 53.00 | 149.99 |
| 1973 .... | 61.00 | 156.16 | 23.00 | 58.88 | 53.00 | 135.68 |
| 1975 .... | 73.95 | 139.03 | 26.00 | 48.88 | 59.00 | 110.92 |
| 1977 .... | 93.16 | 153.71 | 26.00 | 42.90 | 62.00 | 102.30 |
| 1979 .... | 103.00 | 140.08 | 26.00 | 35.36 | 71.00 | 96.56 |
| 1981 .... | 150.63 | 159.67 | 37.92 | 40.20 | 122.88 | 130.25 |
| 1982 .... | 166.00 | 170.98 | 40.00 | 41.20 | 130.00 | 133.90 |
| 1983 .... | 173.00 | 176.46 | 45.60 | 46.51 | 135.00 | 137.70 |
| 1984 .... | 178.00 | 178.00 | 52.36 | 52.36 | 142.00 | 142.00 |

[1]Prices prior to 1973 are reported as of 2/65, 2/67, 2/69, and 2/71. 1973–84 prices are average annual price.
[2]Beryllium powder is 97 pct Be.
[3]Oxide is powder form in lots of 10,000 lb.
[4]Master alloy contains 4 pct Be.

## BERYL ORE MARKETS

Beryl ore prices gradually rose in 1975–80, then abruptly increased in 1981, achieving a peak in 1982. The average market price range for imported beryl ore in 1984 was \$130 to \$147 per short ton unit[4] of beryl ore containing an average 10 pct BeO (*6*). This price includes insurance and shipping costs to U.S. ports. The market price range of 1 mt beryl ore containing an average 10 pct BeO was \$1,433 to \$1,621.

Published market prices are quoted for beryl ore that contains at least 10 pct BeO. However, beryl ore sold on the market ranges from 10 to 12 pct BeO with the quoted price adjusted for beryl ore containing BeO grades higher than 10 pct. Table 2 shows the price history of beryl ore for 1980–84.

Brazilian beryl ore production increased over the period 1975–83. The average annual rate of growth for the 9-yr period was 6.8 pct. The largest increases in beryl ore production occurred in 1978 (64.2 pct) and 1981 (55.0 pct). Argentina's beryl ore production, however, has declined since 1975. Figure 3 represents the beryl ore production for Argentina and Brazil.

The United States exports no bertrandite or beryl ore.

[4]Short ton unit (stu) equals the amount of material that contains 20 lb BeO. At a 10-pct-BeO grade, 200 lb material is purchased for \$130/stu; therefore, 1 mt beryl ore containing 10 pct BeO will cost \$1,433.

**Table 2.—Average actual prices of beryl ore containing 10 pct BeO[1]**

(U.S. dollars per metric ton)

| | |
|---|---|
| 1980 ............. | 937.00 |
| 1981 ............. | 1,212.60 |
| 1982 ............. | 1,333.90 |
| 1983 ............. | 1,289.80 |
| 1984 ............. | 1,212.00 |

[1]Estimated from price ranges published monthly in the Engineering and Mining Journal.

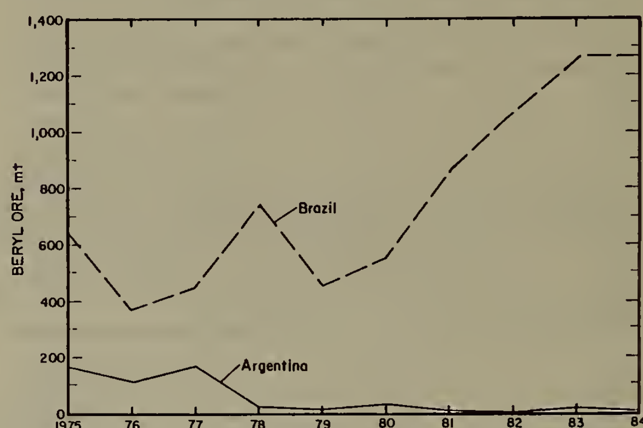


**FIGURE 3.—Beryl ore production in Brazil and Argentina.**

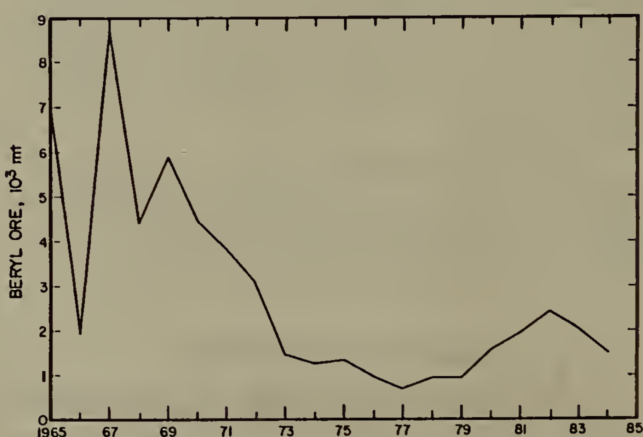


**FIGURE 4.—U.S. beryl ore imports.**

Brazil, the world's third largest producer of beryl ore, exports its ore primarily to the United States, with lesser amounts to Japan and Western Europe.

Several large entities in the United States (the U.S. Government, Brush Wellman Inc., and Cabot Corp.) have purchased the majority of imported beryl ore in the past; however, the U.S. Government has not purchased beryl ore for the strategic minerals stockpile since 1974.

U.S. reliance on imported beryl ore declined from 1969 to 1977; an increase in importation occurred from 1978 to 1982. Beryl ore imports are historically presented in figure 4.

## WORLD BERYLLIUM STATISTICS

### PRODUCTION

Among contributors to world beryllium production are Brazil, China, Mozambique, Portugal, the Republic of South Africa, Rwanda, the U.S.S.R., the United States, and Zimbabwe. In 1983, market economy countries contributed 9.4 pct of the total 415 mt of beryllium contained in ores produced by foreign nations. China and the U.S.S.R. represent 14.0 pct and 18.3 pct, respectively, of the total world production. The United States supplied 58.3 pct of total production. U.S. beryllium production data are not shown in world production figures prior to 1980. World production of beryllium for 1975–84 is shown in table 3.

**Table 3.—World beryllium production, 1975–84 (*8*)[1]**
(Metric tons)

| | | | |
|---|---|---|---|
| 1975 | 129 | 1980 | 382 |
| 1976 | 110 | 1981 | 371 |
| 1977 | 97 | 1982 | 312 |
| 1978 | 112 | 1983 | 414 |
| 1979 | 112 | 1984 | 409 |

[1]Does not include production from the United States prior to 1980.

### TRADE

The United States exports and imports beryllium products in wrought, unwrought, alloy, waste, and scrap forms. Exact chemical and physical compositions of beryllium exports and imports are unknown. The amount of beryllium in various forms exported between 1975 and 1983 ranged from a low of 16.9 mt in 1975 to a high of 72.8 mt in 1977. Over the same period, the total value of the various exported beryllium products increased relative to the total amount exported. Changes in the ratio of wrought products to unwrought, alloy, waste, and scrap beryllium affect the value of these exports.

The United States imports beryllium in various forms from Brazil, Mexico, Canada, France, the Federal Republic of Germany, and the United Kingdom. Figure 5 presents U.S. beryllium exports and imports for 1975–83. As shown

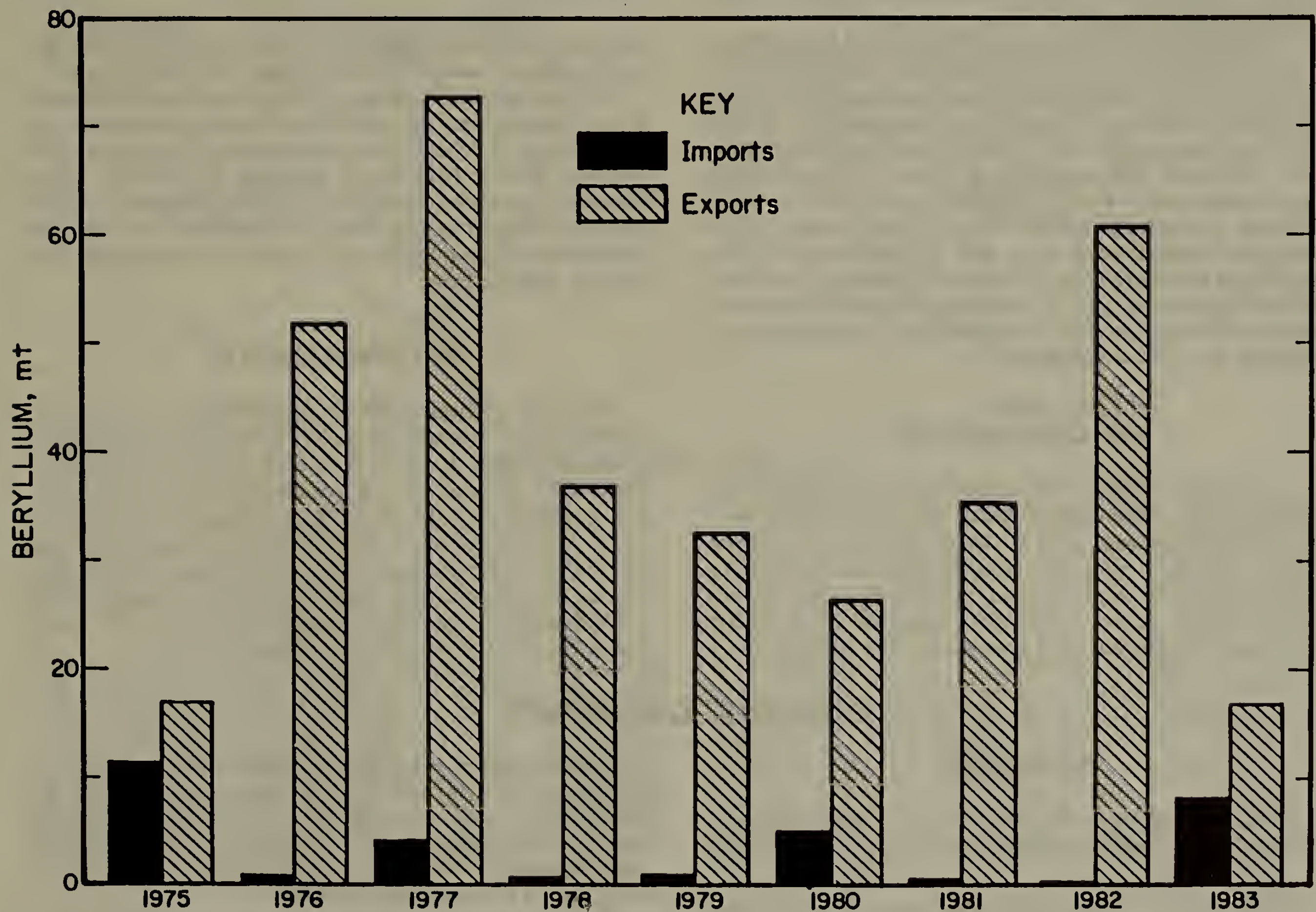


FIGURE 5.—U.S. imports and exports of beryllium in wrought and unwrought forms.

Table 4.—Comparisons of domestic beryllium import and export values, and balance of trade

(Thousand U.S. dollars)

| Year | Exports | Imports | Balance of trade |
|---|---|---|---|
| 1975 | 1,152 | 179 | +973 |
| 1976 | 1,756 | 3 | +1,753 |
| 1977 | 1,911 | 36 | +1,875 |
| 1978 | 1,985 | 11 | +1,974 |
| 1979 | 3,686 | 9 | +3,677 |
| 1980 | 3,867 | 237 | +3,630 |
| 1981 | 3,094 | 21 | +3,073 |
| 1982 | 3,696 | 11 | +3,685 |
| 1983 | 2,693 | 111 | +2,582 |

in table 4, the value of beryllium exports less imports is positive; however, the positive balance of trade is partly offset by the cost of imported beryl ore. The export and import values are not solely attributable to beryllium content since some forms of beryllium products included in total exports and imports contain other minerals such as copper and aluminum.

The United States has given preference to imports from most-favored-nations.[5] Wrought beryllium products imported from MFN's have an ad valorem import duty of 9 pct, while the same products from non-MFN's are levied an ad valorem import duty of 45 pct. No duty has been imposed on imports of ore and concentrate; thus an incentive exists for the importation of ore and ore concentrates into the United States. (Because there is no duty on imported ores and concentrates, import duties are not reflected in the beryl ore availability analysis.)

The amount of beryllium imported by the United States as a percentage of total U.S. consumption is low. (However, imported beryl ore accounts for about one-third of domestic beryllium production.) In figure 6, a comparison of U.S. total beryllium consumption with total refined beryllium importation indicates that generally a rise or fall in consumption corresponds to a rise or fall in importation. In 1978, however, the general pattern was broken—a rise in consumption corresponded to a fall in importation. This anomaly is attributed to an increase in funding of military and aerospace programs in the previous several years and subsequent response of the domestic beryllium industry in the form of increased production.

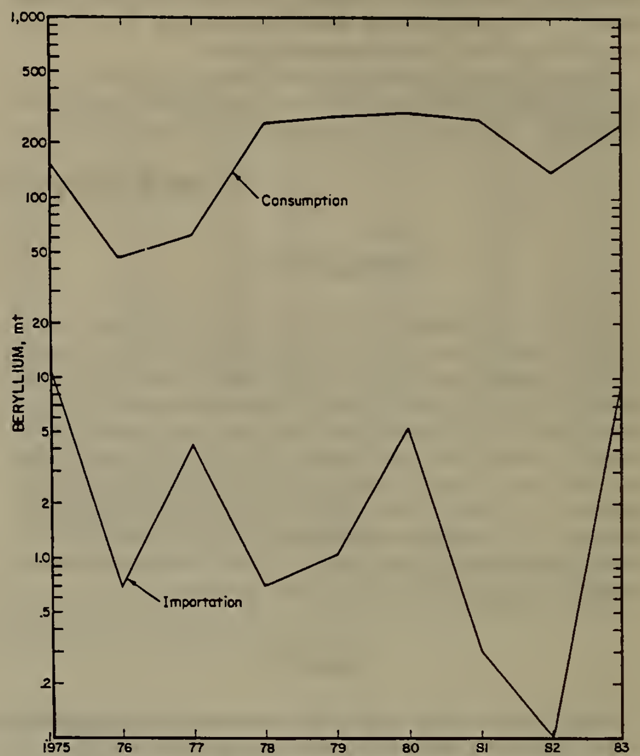

FIGURE 6.—U.S. beryllium consumption and importation.

## U.S. CONSUMPTION

In the early 1970's, alloys constituted more than half of total U.S. beryllium consumption. The electrical and electronic component segments of the beryllium industry use beryllium in both alloy and oxide forms and consume the largest portion of total beryllium produced in the United States. Other major industrial segments that utilize beryllium are nuclear and aerospace. The proportionate amount of beryllium consumed within each of the four sectors remained relatively stable from 1975 through 84.

Technological advancements have contributed a number of new applications for beryllium, thereby broadening its market base. U.S. beryllium consumption showed an overall increase during 1975–84, a decrease in 1976–77 being followed by a sharp increase in 1978–79. Figure 7 shows total beryllium consumed by the United States and the percentages of the total for each of the four segments of commercial applications.

## FUTURE MARKETS

Future beryllium markets essentially will flourish in technologically oriented countries. The Bureau of Mines has made conservative projections of U.S. beryllium demand for 1983–2000. Estimated average annual increase in beryllium demand is 1.5 pct (*9*). Within the major beryllium industry sectors, nuclear industries are expected to increase demand 1.1 pct; aerospace, 1.9 pct; electrical, 1.2 pct; electronics, 2.9 pct; and other industries, 2.9 pct. Projected total world demand for beryllium in the year 2000 is 898 mt, of which the United States represents 61.7 pct.

# ECONOMIC DISCUSSION

## BERYL ORE

Brazil's beryl ore industry consists of many nonorganized miners and several mining companies. The Brazilian economy has sustained a high inflation rate in recent years, and since 1982 the value of Brazilian cruzeiros has decreased relative to U.S dollars. As a result, the increased number of cruzeiros obtained for each U.S. dollar has induced producers to increase production and exportation of beryl ore to the United States.

The limited number of beryl ore buyers in the United States has a monopsonistic influence on the market price

[5]Most-favored-nations (MFN's) consist of most nations of the world selected in negotiations held in Tokyo in 1979. These nations receive lower tariff rates than non-MFN's.

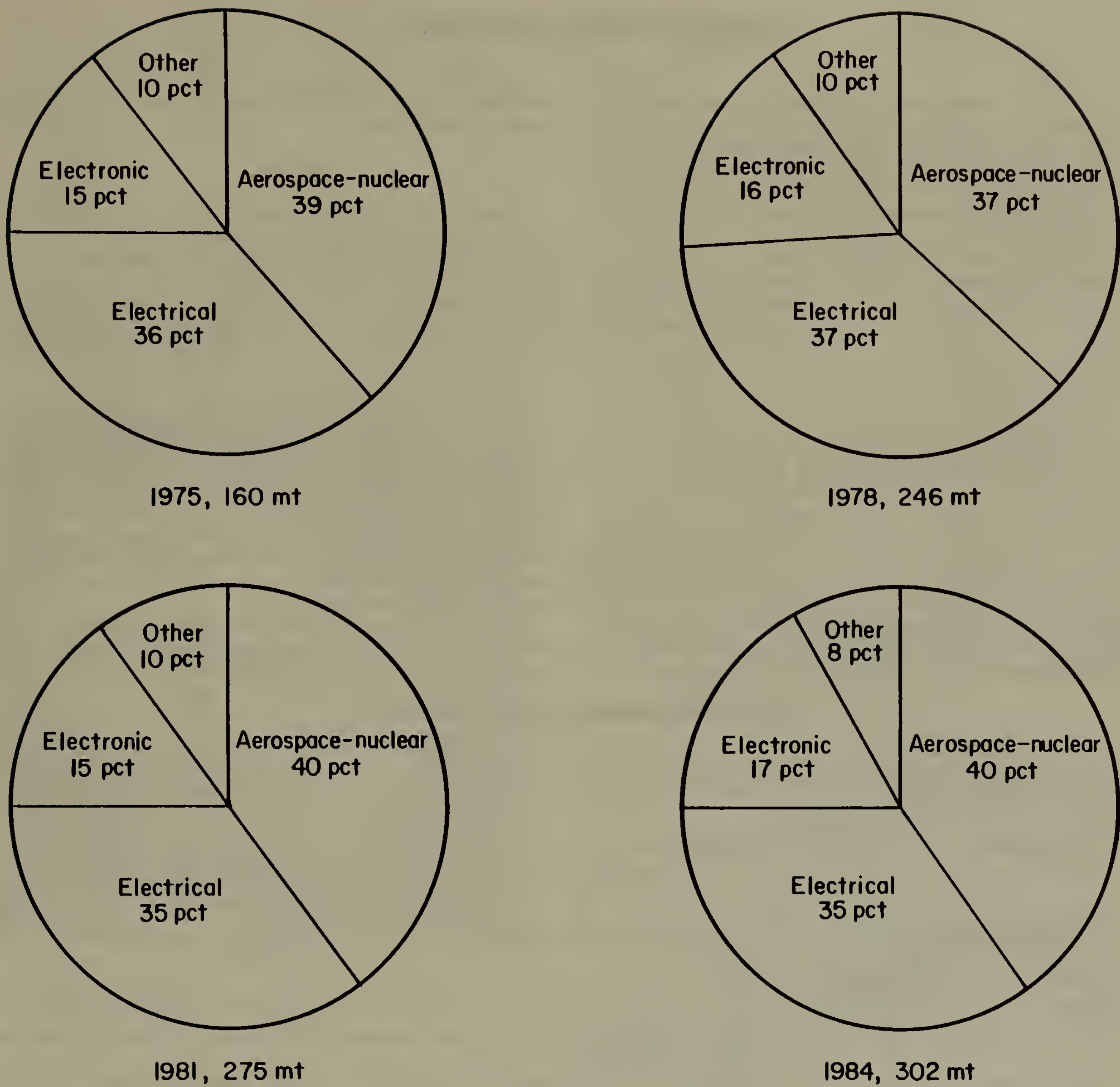


**FIGURE 7.—U.S. beryllium consumption.**

of beryl ore, effectively establishing a price on which beryl ore sellers have little influence. In addition, the large number of Brazilian ore producers and the devaluation of the cruzeiro have ensured a sufficient supply of beryl ore at a steady price. In fact, while Brazilian beryl ore production increased significantly from 1979 to 1984 at an average annual rate of 18.5 pct, the market price for beryl ore imported by the United States decreased after 1982.

## BERYLLIUM

A number of factors inherent in the beryllium industry may affect the amount of beryllium available in the future. In the United States, a paucity of competition in each stage of production and a monopoly in the intermediate stages characterize the beryllium industry. After 1969, when Brush Wellman Inc. became the only fully integrated producer of beryllium in the United States, constant-dollar prices for beryllium products declined (table 1). As of 1984, constant-dollar prices had not reached the price level of 1969. The upward trend in beryllium powder prices after 1975 may reflect the upward trend of beryllium consumption in the United States since 1975.

# GEOLOGY AND RESOURCES

Within the earth's crust, beryllium has been identified in at least 56 minerals, about half of which contain in excess of 1 pct Be (*2, 10*). Beryl, bertrandite, phenacite, helvite, and barylite are the major minerals that are prospected for by beryllium producers. Bertrandite and beryl are currently the only beryllium minerals mined among MEC's for the production of beryllium concentrates.

Until the discovery and development of the large Spor Mountain bertrandite property in Utah, beryl was the primary mineral used in the production of beryllium concentrates. Although beryl occurrences have been identified in many areas throughout the world, lack of data on most of these areas precludes their inclusion in this study. Properties investigaged in this study are listed in table 5.

Over 29,000 mt Be (beryllium metal) is contained in the seven producing and nonproducing operations that were cost-evaluated in this study (table 6). An estimated 3,900 mt Be is contained in ore from the deposits not evaluated; approximately 25 pct of this estimate is available as a byproduct from nonproducing primary mica and tantalum deposits. According to Steven Zajac, Hanna Mining Co., in the case of the nonevaluated operations in Canada, the resource and contained beryllium figures for Canada are probably understated. Additionally, data from CPEC's, specifically the U.S.S.R. and China, are unobtainable. All indications are that these countries contain major beryllium reserves and that the U.S.S.R. is a major producer and consumer of beryllium.

## BERYL

Beryl ($Be_3Al_2Si_6O_{18}$) is a hard, generally green-colored mineral that contains an equivalent of 14 pct BeO. Beryl has been mined for many centuries for its gem stone qualities but has only been utilized for its beryllium metal content since the 1930's. Beryl is usually found in pegmatites and granites but has also been found in mica schists associated with tin ores. The most widely mined beryl-rich rocks in the world are complex pegmatites.

Brazil is the largest producer of beryl among MEC's. Over 106 Mmt beryl ore containing over 15,000 mt Be was estimated for the producing and nonproducing properties evaluated in Brazil (table 6). Almost 99 pct of the contained beryllium is available from the State of Minas Gerais (fig. 8). The beryl-rich pegmatites are tabular and lenticular in shape and differ greatly in size and structure throughout the mining districts. Most of the commercial pegmatites are near schist-granite contacts in the east-central and northeastern part of the country (*11*).

A similarity among commercial-grade pegmatites in Brazil is the fact that they are all complex-zoned or heterogeneous pegmatites. Heterogeneous pegmatites are

**Table 5.—Beryllium-bearing deposits and regions**

| Country and State or deposit name | Owner | Production status[1] | Evaluation status[2] | Comments |
|---|---|---|---|---|
| Argentina: Las Tapias | Juan and Thomas Andino | N | N | Inoperative since 1978; resource data calculated at the inferred level. |
| Brazil: | | | | |
| Cascavel-Cristais | Private land owners | N | Y | Inactive because of low demand. |
| Minas Gerais | ..do | P | Y | Nonmechanized and semimechanized mining operations; evaluated as 2 distinct operations. |
| Picui-Parelhas | ..do | P | Y | None. |
| Quixeramobim-Solonopole | Private land owners and some government land. | N | Y | Most higher grade ore has been exhausted. |
| Southern Bahia | Private land owners | P | Y | None. |
| Canada: | | | | |
| Bernic Lake | Tantalum Mining Corp., owned by Manitoba Government (25 pct), Kawecki Berylco (37.5 pct), and Hudson Bay Mining (37.5 pct). | N | N | Primary tantalum property that was shut down. |
| Hellroaring Creek | Bearcat Exploration Ltd. and Colt Exploration Ltd. | N | N | Low-grade prospect, yet highly promoted. |
| Seal Lake | Unknown | N | N | Prospect. |
| Strange Lake | Iron Ore Co. of Canada | N | N | Undeveloped primary yttrium property; disputes exist concerning property ownership. |
| Thor Lake | Highwood Resources | N | N | Currently evaluating ore and developing bench-scale processing plant. |
| United States: | | | | |
| Custer, SD | Numerous owners | N | N | Past producer of byproduct beryl. |
| Hill City, SD | ..do | N | N | Do. |
| Keystone, SD | ..do | N | N | Do. |
| Mount Antero, CO | North American Beryllium Corp. | N | N | Undeveloped prospect. |
| Mount Wheeler, NV | Mt. Wheeler Mines, Inc., subsidiary of National Treasure Mines Co. | N | N | Insufficient grades of primary tungsten were encountered during development work; development ceased in 1950's. |
| Muscovite Mine, ID | Unknown | N | N | Past producer of mica and byproduct beryl. |
| Railway Dike, WA | Meridian Land and Mining Co. and Burlington Northern. | N | Y | Nonproducer. |
| Spor Mountain, UT | Brush Wellman Inc. | P | Y | None. |
| Yellow Hammer, UT | American Consolidated Mining Co. | N | N | Past producer of byproduct beryl. |

[1]N – nonproducer; P – producer.
[2]Y – included in cost and reserve analysis; N – only included in reserve analyses when data were available.

Table 6.—Market economy country beryllium resources

| Cost analysis status | Number of operations: Producing | Number of operations: Nonproducing | In situ ore, $10^3$ mt | In situ BeO grade[1] | Contained Be,[2] mt |
|---|---|---|---|---|---|
| Evaluated: | | | | | |
| Brazil | 3 | 2 | 106,047 | 0.0004 | 15,260 |
| United States | [3]1 | 1 | 5,700 | .0067 | 13,740 |
| Subtotal or wtd av | 4 | 3 | 111,747 | .0007 | 29,000 |
| Not evaluated: | | | | | |
| Argentina | 0 | 1 | [4]162 | .0002 | 10 |
| Canada | 0 | 5 | 1,284 | .0062 | 2,860 |
| United States | 0 | 7 | 4,775 | .0006 | 1,030 |
| Subtotal or wtd av | 0 | 13 | 6,221 | .0017 | 3,900 |
| Grand total or wtd av | 4 | 16 | 117,968 | .0008 | 32,900 |

[1]Weight-averaged by country.
[2]The product of in situ ore times in situ grade; to determine Be grade from BeO, divide BeO value by 2.78.
[3]Spor Mountain bertrandite mine.
[4]Inferred resource; demonstrated resources not available.

FIGURE 8.—Location of South American beryllium deposits.

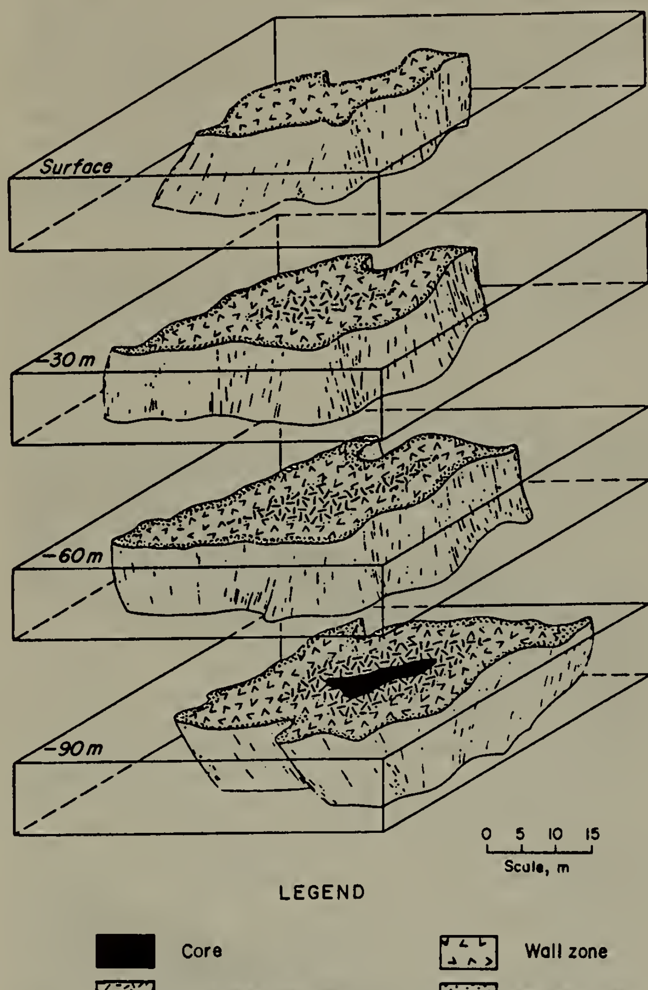

FIGURE 9.—Geologic block diagram of a zoned pegmatite.

generally composed of three identified zones which are progressively coarser grained toward the quartz nucleus (fig. 9). The intermediate zone of producing pegmatites, which borders the core, contains beryl as well as spodumene, columbite-tantalite, cassiterite, and semiprecious gem stones. Because of the resistance to weathering of the quartz core, heterogeneous pegmatites can often be recognized in the field as topographic highs (*12*).

The principal beryl-producing areas of Brazil are the Rio Doce Valley and adjacent areas in the State of Minas Gerais (Minas Gerais operations), the Campina Grande district in the State of Rio Grande do Norte (Picui-Parelhas operations), the Critais-Berilandia district in the State of Ceara (Cascavel-Cristais and Quixeramobim-Solonopole operations), and the Jequitinhonha River Province (Southern Bahia operations) in the State of Bahia (fig. 8) (*10*).

Similar commercial pegmatite zones have been mined in parts of Africa, Argentina, Australia, and India. The Las Tapias district of Argentina (table 5) used to be one of the larger South American producers, but no significant amount of beryl has been mined there since 1978.

Commercial beryl-rich pegmatites in the United States are scattered throughout the Appalachians from Alabama to Maine. Several deposits have also been mined in the Black Hills of South Dakota and throughout the Colorado Rocky Mountains (table 5). Except for a few, small, family operations, none currently produce beryl as a primary commodity. Although beryl may occasionally be produced in the

United States as well as in some foreign countries, Brazilian beryl mining far outweighs that of any other MEC in terms of production.

## BERTRANDITE

Bertrandite [$Be_4Si_2O_7(OH)_2$] was discovered in volcanic tuff beds of the Spor Mountain area of west-cental Utah in 1959. It is a colorless mineral with no visible physical characteristics to aid in its identification (*13*). Exploration and development of the ore body took place in the 1960's, and after development and construction of a beryllium hydroxide beneficiation plant, Spor Mountain became the largest source of beryllium in the United States. Brush Wellman is also the largest producer of beryllium concentrate [$Be(OH)_2$] in all market economy countries.

The Spor Mountain bertrandite occurs in a water-laid tuff underlying Tertiary rhyolites and unconformably overlying Paleozoic carbonates. The carbonates and the overlying tuff dip to the west (fig. 10). Clasts of the carbonate occur locally within the tuff. The tuff served as an ideal host to laterally or upwardly migrating fluorine-rich hydrothermal fluids; decreasing temperature and fluorine concentrations allowed the precipation of bertrandite. In addition to bertrandite, fluorspar, manganese oxides, and uranophane are contained in the tuff beds (*2*).

The Spor Mountain deposit has proven ore reserves of 5.3 Mmt at a grade of 0.690 pct BeO (*14*). According to Stephen Zenczak, Brush Wellman Inc., the attitude of this stratiform deposit is such that deeper mining down dip could increase the reserve tonnage if the depletion of established reserves warranted further development.

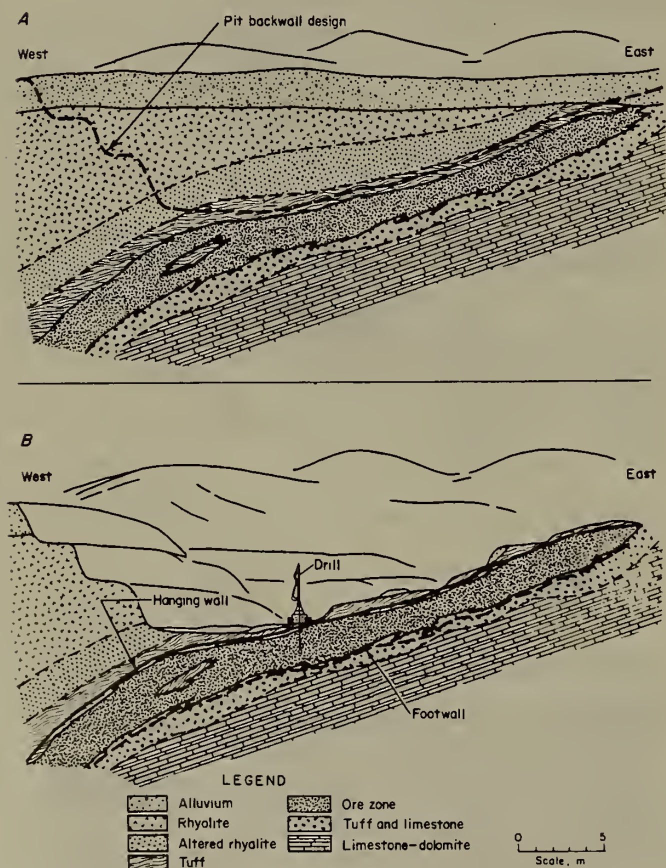


**FIGURE 10.—Spor Mountain, UT: *A*, Cross section of bertrandite ore body; *B*, geologic cross section and secondary drilling.**

## OTHER BERYLLIUM MINERALS

Beryllium resource estimates in this study do not account for potential resources from many known beryllium occurrences. Several North American deposits containing undetermined beryllium resources were not evaluated because of a lack of geologic, engineering, and cost data; however, ongoing development work on Canada's Thor Lake and Strange Lake deposits may add significantly to future beryllium resource estimates.

Thor Lake is a large beryllium deposit currently being developed in the Yellowknife area of the Northwest Territory, Canada (fig. 11); it is owned by Highwood Resources Ltd. of Calgary. Several metasomatically altered units associated with an Archean alkaline-syenite intrusive complex contain rare-earth elements, columbium, zirconium, and tantalum minerals as well as phenacite ($Be_2SiO_4$), a beryllium mineral with potential for commercial development. In 1984, both gallium and gadolinite ($Be_2FeY_2Si_2O_{10}$) were also discovered in quantities that may be economically recoverable (*15*).

At least 450,000 mt ore containing 1.4 pct BeO have been outlined in the "T" zone, and over 1.3 Mmt ore grading 0.66 pct BeO is available south of the zone (*16–17*). Preliminary metallurgical studies indicate that recoveries of 85 to 90 pct can be obtained, yielding a product containing 10 to 13 pct BeO. Thor Lake could produce beryllium concentrates by 1987 (*15*). It has been speculated by Highwood Resources president Thomas Grenville that beryllium concentrates from Thor Lake would be sold in Europe and in Asia.

The Strange Lake yttrium-zirconium property (table 5; fig. 11) is situated on the border of Newfoundland and

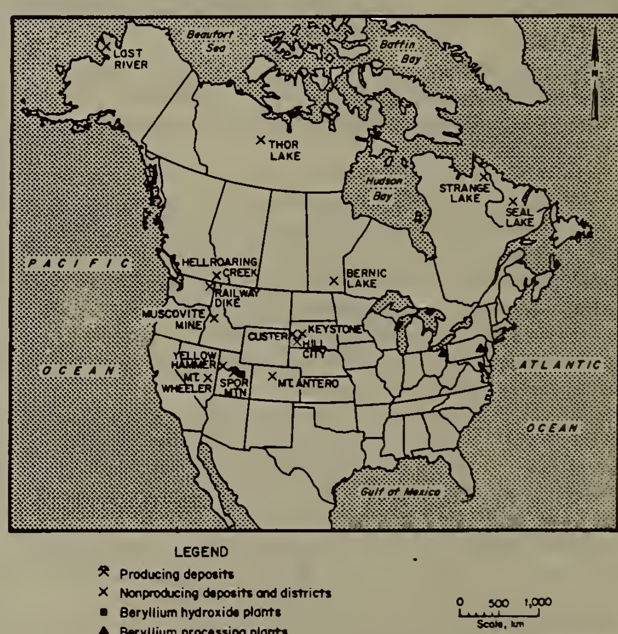


**FIGURE 11.—Location of North American beryllium deposits and processing plants.**

Quebec, about 100 miles northeast of Shefferville, Newfoundland, and contains large amounts of beryllium, rare-earth elements, and columbium. A beryllium phosphate mineral, herderite [$CaBe(F,OH)PO_4$], has also been identified there (*15*). The Strange Lake deposit is owned by the Iron Ore Co. of Canada, a subsidiary of the M.A. Hanna Mining Co., Cleveland, OH. Because of a conflict over the mineral rights to this property, resource and in situ grade data have not been released.

Large concentrations of two beryllium minerals, barylite ($Be_2BaSi_2O_7$) and eudidymite [$(NaBeSi_3O_7)OH$], have been reported near Seal Lake in Labrador. The only other significant beryllium occurrence in Canada is the Hellroaring Creek prospect west of Kimberley, British Columbia. It is owned by Bearcat Exploration Ltd. (80 pct) and Colt Exploration Ltd. (20 pct) and may contain up to 500,000 mt of 0.1 pct BeO (*15*).

A mineralized area speculated to have commercial beryllium potential is the Lost River tin deposit on the western edge of the Seward Peninsula in Alaska (fig. 11). Tin mineralization is associated with Late Cretaceous granitic intrusions in a massive Ordovician limestone. Beryllium mineralization, primarily chrysoberyl ($BeAl_2O_4$), is hosted by fluorite-mica veins distributed throughout the deposit. The veining may not be related to processes that produced the tin-bearing skarn and greissen (*18*). Samples analyzed by the Bureau of Mines averaged 0.12 to 0.13 pct BeO (*18*). No beryllium mineral resource data are available for the Lost River deposit.

The Mount Wheeler Mine in White Pine County, NV, is found in the Wheeler Limestone Member of the Cambrian age Pioche Shale Formation (fig. 11). The lower portions of this limestone unit have been slightly altered, owing probably to an underlying granitic sill. Beryllium mineralization is in the form of bertrandite, phenacite, and chrysoberyl. Over 71,000 mt of 1.00 pct BeO resources have been demonstrated, with almost 150,000 mt of 1.00 pct BeO identified. Renewed speculation and investigations into the Mount Wheeler deposit may define larger resources of beryllium minerals, tungsten, and other products.

## BERYLLIUM MINING AND BENEFICIATION

The United States is the largest producer and consumer of beryllium among MEC's. The Spor Mountain bertrandite mine in Utah, owned and operated by Brush Wellman Inc., is the only source of beryllium hydroxide (an intermediate beryllium compound needed to make beryllium products) in the United States. Many domestic pegmatite districts have supplied beryl ore in the past, but none are currently operating.

All remaining beryllium concentrates produced in market economy countries are derived from the mining of beryl-rich pegmatites. Brazil is the largest supplier of beryl ore to the United States. The following section will focus on the mining and processing of beryl and bertrandite.

### BERYL MINING AND PROCESSING IN BRAZIL

Most of the beryl ore produced in MEC's is from Brazil, where labor-intensive, pick-and-shovel mining of weathered pegmatites is the primary mining method employed. Garimpeiros (laborers) perform all of the mining and cobbing of the beryl ore. Since the garimpeiros mine on privately owned lands and sell ore directly to ore buyers, data regarding mining methods and production are scarce.

Pegmatite mining in Brazil consists essentially of stoping into exposed, weathered pegmatites with picks and shovels. Mines are established wherever beryl-rich pegmatites exist. If material is encountered that cannot be mined with picks and shovels, the garimpeiros will bypass it and start a stope in a more easily mined zone. Each stope is worked by three to five men who pick beryl crystals out of the host rock and muck out the waste. Other garimpeiros (usually women and children) sort through the mucked-out material for beryl crystals that were overlooked.

Stopes opened in the weathered zones are approximately 1.5 m high and 1.0 m wide. A "mine" can contain as many as 40 stopes. It is assumed that all beryl contained in the mined-out material is recovered for hand cobbing. Approximately 10 pct of the beryl is lost by hand cobbing. The upgraded (hand-cobbed) ore contains an equivalent of 6 to 8 pct BeO.

In the Picui-Parelhas district, a few primitive shaft and drift operations are employed in the weathered pegmatites. The shafts are usually sunk by digging out the soft kaolinized clay. When the beryl-rich zone of the pegmatites is encountered, garimpeiros drift along this zone to extract the pegmatite.

Almost 10 pct of the beryl production from Minas Gerais is from operations that utilize drilling and blasting in the pegmatite mining. It is estimated that several of these mines can produce about 50 mt/yr beryl ore (grading 6 pct BeO).

Beryl ore from the mining districts is purchased periodically by representatives of the ore buyers, who transport it to nearby markets where the concentrates (approximately 6 to 8 pct BeO) are further upgraded. This upgrading consists of additional hand cobbing of the beryl and achieves an average estimated recovery of 96 pct. The final beryl ore contains at least 10 pct BeO and is eventually shipped to Rio de Janeiro or other ports for export. It is shipped in 20- to 40-st lots with the lump ore being approximately 3 by 5 cm in size and packed in burlap bags.

Most of the beryl produced from the weathered pegmatites in Brazil is used for industrial purposes and is exported to industrialized nations like the United States, Japan, and France. The largest U.S. buyer of exported beryl ore in Brazil, Cabot Corp., and presumably the other U.S. ore buyers, have facilities in Brazil for the storage and upgrading of beryl ore, according to Alan Berger, Cabot Corp.

### BERTRANDITE MINING AND PROCESSING

Bertrandite is mined at Spor Mountain in Utah and processed at the nearby Delta plant (fig. 11). It is mined from a dipping, stratiform ore body composed primarily of welded and nonwelded tuff. Several open pits with stripping ratios of approximately 12:1 have been developed to mine this uniform ore body.

Overburden is removed by local contractors in the winter and spring to take advantage of cooler weather. Push

dozers and scrapers remove most of the unconsolidated overburden, leaving about 7 ft of cover. Directly underlying the alluvium is a rhyolite which must be blasted; the blasted material is removed with front-end loaders and off-road haulage trucks.

After most of the overburden stripping is completed, secondary drilling on 25-ft centers is performed to further delineate the ore body. Samples and berylometer readings are taken to establish the hanging-wall and foot-wall cutoffs. The remaining 7 ft of cover is then removed to expose the ore zone. Because of an irregular BeO grade throughout the ore zone, ore is systematically stockpiled so that a consistent grade of material can be sent to the mill.

Mining consists of ripping and loading the exposed tuff. Ripping is performed with a bulldozer, and subsequent loading is performed with a self-loading scraper. Ore is generally mined from predetermined areas of the ore body so that stockpiling can be achieved.

The stockpiled ore is then drilled on 20-ft centers. An assay map is generated to identify grade distributions throughout the stockpile. The ore is then selectively recovered and trucked to the Brush Wellman's Delta plant in Lynndyl, UT, about 50 miles east of the deposit.

The Delta plant is the only commercial facility in the United States that extracts beryllium values from beryllium concentrates (beryl ore and bertrandite concentrates). The plant, which was designed to process 350 st ore (318 mt, containing 0.7 mt beryllium metal) daily (fig. 12), went on-line in 1969 and was modified in 1978 to accommodate the extraction and recovery of beryllium from imported beryl ore.

Extracting beryllium consists of wet-milling the ore to provide a slurry of minus 20-mesh particles. The slurry is leached using $H_2SO_4$ at temperatures near boiling point to solubilize beryllium contained in the bertrandite. A leach liquor containing $BeSO_4$ is separated from the solids by countercurrent decantation (CCD) thickener processes.

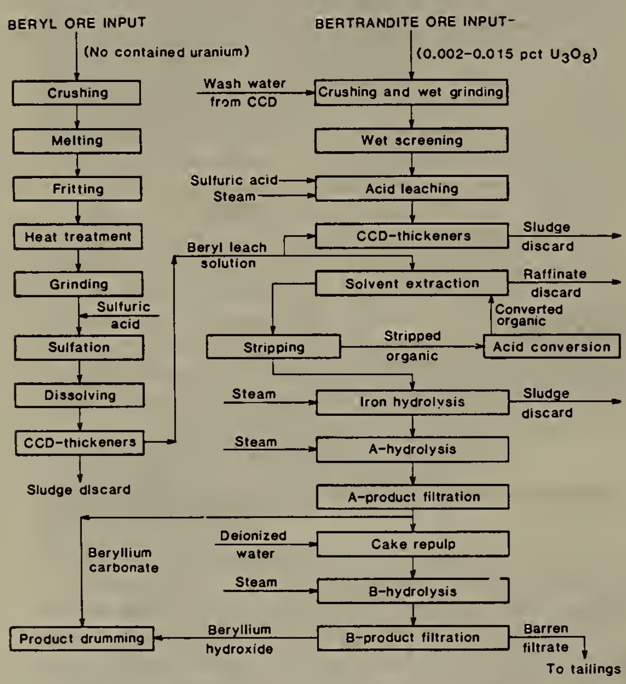


FIGURE 12.—Delta plant flowsheet. (Courtesy, Brush Wellman, Inc.)

Beryllium concentrate is produced from the leach liquor by countercurrent solvent extraction. The beryllium-extracting solution is composed of di(2-ethylhexyl) $H_3PO_4$ in kerosene. The rate of the beryllium solvent extraction is accelerated by heating the extractant and the leach solution.

The organic phase is stripped of its beryllium content with aqueous $(NH_4)_2CO_3$. Heating this solution to about 70° C precipitates the iron and aluminum as hydroxides or basic carbonates, which are then removed by filtration. The stripped organic phase is then reacidified using $H_2SO_4$ to regenerate $H_3PO_4$ for return to the solvent extraction step.

Heating of the beryllium carbonate solution causes precipitation of the beryllium carbonate, $2BeCO3.Be(OH)_2$. This process releases $CO_2$ and ammonia, which are recovered for recycling. Further heating liberates the remaining $CO_2$ for recycling. The $Be(OH)_2$ product is dewatered by filtration and transported to Brush Wellman's Elmore, OH, facility for processing into metal, beryllium-copper alloy, or beryllia ceramic products. Approximately 80 pct of the beryllium value in the bertrandite is recovered by this process (*2*).

## BERYL FLOTATION AND BERYL ORE EXTRACTION METHODS

Before beryllium was available from the large Spor Mountain bertrandite ore body, MEC beryllium was primarily derived from beryl ore. Methodologies involving the flotation of beryl from pegmatite ore and the extraction of beryllium from beryl ore (beryl concentrate from pegmatite ore) are discussed in this section.

### Beryl Flotation From Pegmatite Ore

Beryl is generally mined from pegmatites. Because its specific gravity is similar to that of quartz and feldspar, flotation provides a much better means for recovering beryl than gravity separation methods. Similar methods used in separating feldspar from quartz and mica are applicable for the flotation of beryl. The following procedure was derived from a Denver Equipment Co. bulletin (*19*) (fig. 13).

The first step in recovering beryl from pegmatite ore requires grinding the ore. To recover beryl, a minus 35-mesh grind is necessary. The material is then fed through a magnetic or electrostatic separator circuit. This process separates the beryl from other minerals that may be economically recoverable, such as cassiterite and columbite. Desliming of the rod mill discharge is done through a cyclone classifier, which thickens the deslimed sand for subsequent conditioning and mica flotation at 50 pct solids or higher.

Tailings from the mica flotation are conditioned with HF. Flotation of the tailings with an amine acetate collector and an alcohol frother yields a bulk feldspar and beryl concentrate. Subsequent thickening of this concentrate removes excess reagents and water. The concentrate is then stored for batch processing so that the beryl flotation section can be operated under controlled conditions not subject to fluctuations in previous processing and treatment steps.

The bulk concentrate is conditioned with hypochlorite and washed to remove all reagents. The washed solids are conditioned with $H_2SO_4$ and petroleum sulfonate and then

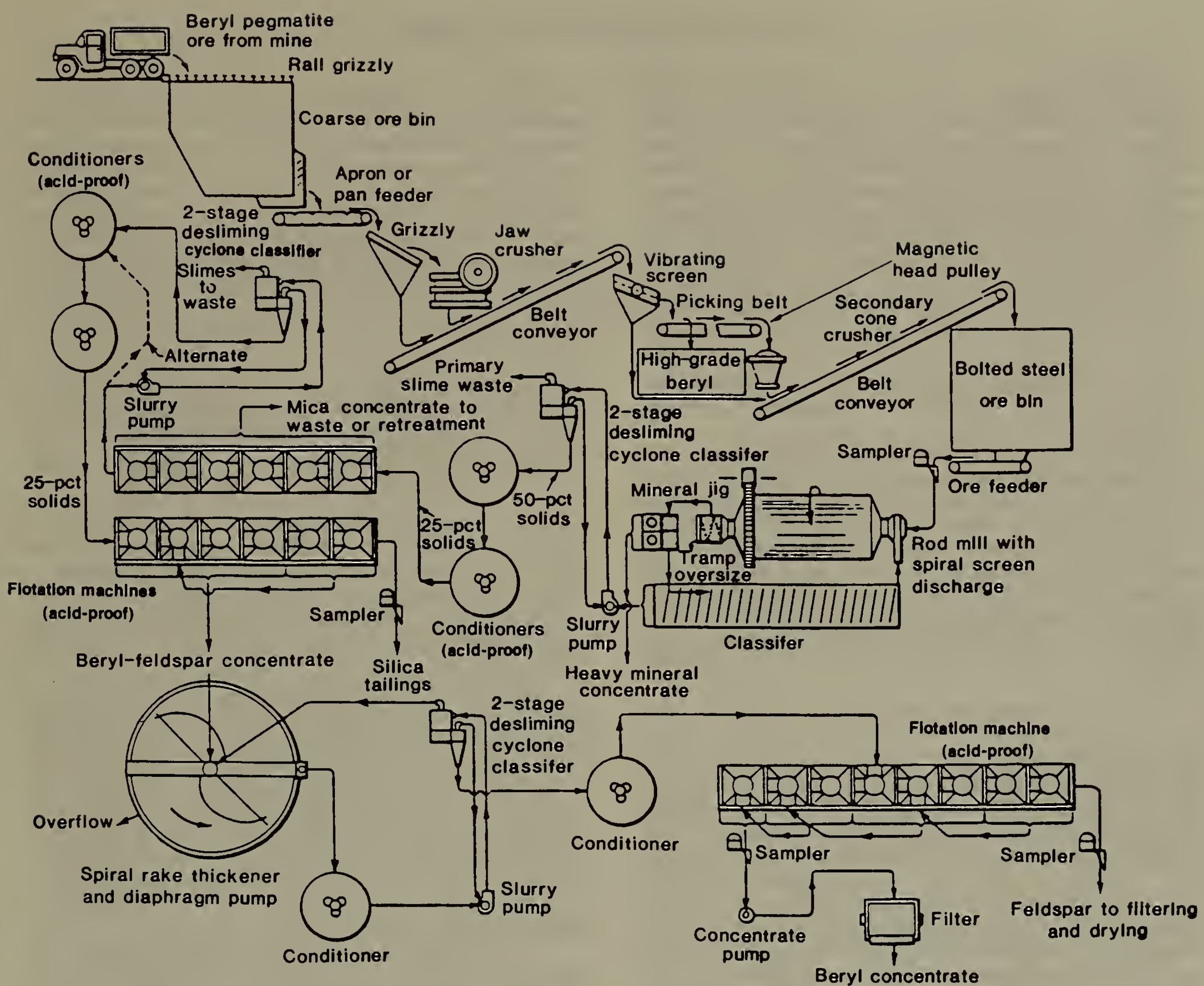


FIGURE 13.—Denver Equipment Co. beryl flotation design. (Courtesy Denver Equipment Co.)

diluted to 20 to 25 pct solids for beryl flotation. The feldspar fraction is depressed as flotation tailings at this juncture. The froth containing beryl is cleaned, several times if necessary, to raise the grade to 10 pct BeO and is then pumped to a rotary filter.

## Extraction of Beryllium From Beryl Ore

Two methods of beryllium extraction from beryl ore, the fluoride process and the sulfate process, have been used on a commercial scale. The sulfate process is used at Brush Wellman's Delta plant to produce BeO from imported beryl ore. Both processes are designed to recover 80 to 90 pct of the BeO equivalent from the input ore (*2*).

### Fluoride Process

The Copeaux-Kawecki fluoride process consists of heating ground beryl ore with sodium ferric fluoride at 750° C. One of the reaction products of this process, $Na_2BeF_4$, is water soluble, and so $Be(OH)_2$ can be obtained by aqueous leaching. The beryllium extraction yield from this process exceeds 90 pct.

The initial $Be(OH)_2$ product from this roasting process is not pure enough for beryllium product manufacturing. Redissolving the $Be(OH)_2$, adding chelating agents, and then reprecipitating yields a $Be(OH)_2$ product suitable for commercial applications (*2*).

### Sulfate Process

The Kjellgren-Sawyer sulfate process, installed at Brush Wellman's Delta plant, treats beryl ore fed into the beneficiation circuit. The cost of energy for this fusion process requires the beryl ore to average 11 pct BeO equivalent, although recent developments at Brush Wellman's plant allow for a lower grade of ore (greater than 8 pct) to be beneficiated (*2*). A beryl ore feed of a lower grade would be less energy efficient and more costly.

Beryl ore is melted at 1,625° C and then quenched in water. The beryl glass is reheated and then ground to a minus 200-mesh powder. A slurry of the powdered beryl in $H_2SO_4$ is heated to 250° to 300° C to convert the beryllium to a sulfate, which can then be incorporated into the remaining Delta plant beneficiation circuits.

## EVALUATION METHODOLOGY

To develop estimates of the demonstrated resources, grades, and production costs, data on beryl and bertrandite geology, mining engineering, and beneficiation were obtained. For each operation evaluated, actual or estimated capital expenditures for exploration, acquisition, development, mine plant and equipment, and mill plant and equipment were included. The capital costs for the mining and processing facilities include expenditures for mobile and stationary equipment, construction, engineering, infrastructure, and working capital. Infrastructure includes costs for access to the mine and its associated facilities, ports, water supply and treatment, power supply, and personnel accommodations. Working capital is a revolving cash fund intended for covering operating expenses such as labor, supplies, insurance, and taxes.

The initial capital costs for producing mines and developed deposits were depreciated according to the actual investment year. The undepreciated portion was treated as a remaining capital investment in 1984. Reinvestments varied according to capacity, production life, age of facilities, and company philosophy. All costs were originally in January 1982 dollars but have been updated to January 1984 dollars according to local currency factors and individual country inflation indexes, weighted proportionately by the effects of labor, energy, and capital on a countrywide basis.

The total operating cost estimates for beryl operations are a combination of direct and indirect costs. Direct operating costs include mining and maintenance labor, supplies, supervision, payroll overhead, insurance, local taxation, and utilities. Indirect operating costs include technical and clerical labor, administrative costs, maintenance of the facilities, and research. Other costs in the analyses include such standard deductibles as depreciation, depletion, deferred expenses, investment tax credits, and tax loss carry-forwards. Total operating costs for the bertrandite property were not determined because of insufficient data.

After the engineering parameters and associated costs for the evaluated beryl deposits were established, the supply analysis model (SAM) was used to perform economic evaluations pertaining to the availability of beryl ore (*20*).

Specifically, the SAM system is a comprehensive economic evaluation simulator that is used to determine the average total production cost over the estimated life of each operation including a prespecified discounted-cash-flow rate of return (DCFROR) on investments, less all byproduct revenues. This average total cost represents the constant-dollar, long-run price at which the ore must be sold to recapture all costs of beryl production including a prespecified DCFROR.

For this study, rates of return of 0 and 15 pct were specified when determining the long-run cost of beryl ore production over the life of a property. The first rate (0 pct) was used to determine the break-even cost, where revenues are sufficient to cover total investment and production costs over the operation's life but provide no positive rate of return. This rate could reflect commitment to a project that seeks only a market share or where other advantages such as social benefits, foreign capital, technological progress, or expectation of better market prices would offset current profitability. A 0-pct rate of return could be acceptable for government-operated mining ventures. For privately owned enterprises, a more reasonable economic decision-making parameter is that represented by the 15-pct DCFROR. This rate is considered the minimum rate of return sufficient to maintain adequate long-term profitability and attract new capital to the industry.

The SAM program contains a separate tax records file for each country and State and includes all the relevant tax parameters under which a mining firm would operate. These tax parameters were applied to each evaluated mine with the assumption that each operation represents a separate corporate entity. The SAM system also contains a separate file of 12 economic indexes for each country to enable updating of cost estimates for mines and deposits in 95 countries.

Detailed cash-flow analyses were generated for each preproduction and production year of an operation, beginning with the initial year of analysis in 1984. Individual mine analyses were then aggregated to produce a total availability curve for beryl ore. It was constructed as an aggregate of all evaluated beryl ore operations, ordered from those having the lowest average total costs to those having the highest. No availability curve was constructed for bertrandite since there is only one producing operation.

Certain assumptions are inherent to all analyses performed in this report:

1. All mines produce at design capacity throughout the estimated life of the operations, unless they were known to be producing at reduced levels or were temporarily shut down because of depressed market conditions. It was assumed that full capacity could be reached after a 1- to 4-yr preproduction period.
2. Each operation is assumed to be able to sell all of its output at no less than the determined total cost required to obtain at least the minimum specified rate of return.

Some of the deposits evaluated could be prevented from development, forced to reduce production, or forced to close owing to lack of capital, environmental problems or issues, political reasons, a poor economic climate, or other constraints not known at this time.

## OPERATING COSTS

Operating costs, presented in January 1984, U.S. dollars, were estimated for six of the producing and nonproducing mines and deposits discussed in this study (table 7). The cost analyses are based solely on the production of primary beryl ore and bertrandite ore from Brazil and the United States. Costs were gathered during site visits, by contacts with company officials, and from published materials. Where unavailable, operating costs were estimated by standard costing techniques. Costs include mining, milling, processing, transportation, taxes, and royalties. The operating costs presented are weighted averages projected over a mine's life and are calculated in

Table 7.—Estimated operating costs and contained beryl ore in Brazil and the United States[1,2]

| | Number of operations | Contained beryl ore, mt | Mining and processing costs | | Taxes, beryl ore | Total cost | |
|---|---|---|---|---|---|---|---|
| | | | Pegmatite ore | Beryl ore | | 0-pct DCFROR | 15-pct DCFROR |
| Producers: Brazil | 3 | 399,800 | $2.70 | $770 | [3]$110 | $880 | $990 |
| Nonproducers: | | | | | | | |
| Brazil | 2 | 600 | .80 | 1,100 | 220 | 1,430 | [4]1,430 |
| United States | 1 | 8,900 | W | W | W | W | W |

W Withheld to avoid disclosing company proprietary data.
[1]Based on 1982 data; costs updated to 1984 U.S. dollars.
[2]All costs are weight-averaged in terms of dollars per metric ton of pegmatite ore or beryl ore.
[3]Royalty of 15 pct on the value of the mined material that the miners pay to the landowners.
[4]Because of error limits in rounding, variations between 0- and 15-pct DCFROR's values appear to be zero; slightly larger 15-pct value is not reflected in the data when 15-pct DCFROR's are rounded to the nearest $10/mt beryl ore.

dollars per metric ton of pegmatite ore mined ($/mt pegmatite ore), dollars per metric ton of beryl ore produced ($/mt beryl ore, containing 10 pct BeO equivalent), and dollars per metric ton of bertrandite ore mined ($/mt ore).

## BERYL

Most Brazilian production comes from the labor-intensive, nonmechanized mining of weathered pegmatites. The final exported ore contains approximately 10 pct BeO equivalent. All mining and upgrading costs were combined in the mining costs (table 7) for this discussion. Mining costs on a per-ton-of-ore basis for the producing deposits are $2.70 for pegmatite ore (table 7). In dollars per metric ton for beryl ore produced, mining costs are approximately $770. Taxes bring the total cost to $880/mt beryl ore, which also equals the cost estimated at a 0-pct DCFROR. This "break-even" value represents the minimum price for beryllium concentrate that a producer would need in order to cover all production costs with no constant-dollar, long-term profit. The total cost estimated for producing deposits at a 15-pct DCFROR is $990/mt. The average price for imported beryl ore (f.o.b. U.S. port), in 1984 U.S. dollars, is approximately $1,212/mt ($110/stu, 10-pct-BeO equivalent).

Estimated mining costs from the two nonproducing regions of Brazil, on a per-ton-of-ore basis, are $0.80. Mining costs estimated for producing districts are higher than costs estimated for nonproducing districts because explosives and heavy equipment are employed by several mines in the producing districts.

The total cost, per metric ton of beryl ore, is $1,430 for nonproducers from Brazil. This cost is higher among nonproducers than among producing districts because of a lower grade of ore. In Brazil, higher costs are to be expected with relatively lower grade ore because of the labor- intensive upgrading methods utilized as well as the 10-pct-BeO concentrate grade required for exported beryl ore; 10 pct BeO is the lowest grade of beryl ore imported into the United States because it is generally the lowest concentrate grade accepted at Brush Wellman's Delta plant.

The nonproducer evaluated in the United States is a high-cost, underground pegmatite operation. Costs were withheld (table 7) because engineering and cost data collected are confidential.

The published price of $1,212/mt (*6*) for imported beryl ore concentrates was estimated by metal market analysts. This price range includes transportation costs, duties, and insurance associated with shipping the beryl ore.

Many of the miners and ore buyers are paid for recovered tantalite in addition to the small wages paid for recovering beryl. In most cases, were it not for pay realized for tantalite recovery (no data are available for tantalite recoveries), beryl would not be attractive to the miners or the ore buyers, according to Alan Berger, Cabot Corp.

## BERTRANDITE

Operating costs and capital investments were estimated for Brush Wellman's mining and processing facilities. Reserves and feed grade data derived from annual reports, and a general understanding of Brush Wellman's bertrandite mining and beneficiating methods, permitted these costs to be estimated.

$Be(OH)_2$ production at Brush Wellman's Delta plant is derived primarily from bertrandite ore. Although imported beryl ore augments bertrandite in the processing circuits, the amount of beryl ore fed into the circuits may vary from year to year. For this study, a constant beryl ore feed was assumed.

Assuming an average input of 2,465 mt/yr beryl ore through Brush Wellman's Delta mill facilities and assuming an average mill recovery of about 80 pct of the BeO contained in the bertrandite ore, it is estimated that mining costs are approximately $13.50/mt bertrandite ore. The cost of augmenting bertrandite ore with beryl ore is approximately $1,600/mt beryl ore (containing 10 pct BeO). This is the cost for purchasing the beryl ore at Los Angeles, CA, and transporting it to Brush Wellman's facilities. Based on a feed of 99,000 mt/yr bertrandite ore (0.614-pct-BeO feed grade) plus an average beryl ore feed of 2,465 mt/yr, the total operating cost (0-pct DCFROR) for the production of an intermediate $Be(OH)_2$ is estimated to be between $10/lb and $20/lb. This cost represents production of an intermediate product for which no market price is available.

# AVAILABILITY

The total amount of contained beryllium from all sources is approximately 33,000 mt. The Utah bertrandite ore deposit contains approximately 14,000 mt Be, or 42 pct of the total contained beryllium.

Primary beryllium production depends upon availability of both ores and extraction plants. Availability analysis of beryllium at various costs of production is restricted for the following reasons: Only one major beryllium extraction

plant presently operates in the Western Hemisphere; very few extraction plants exist worldwide; and beryllium availability currently relies on the availability of beryl and bertrandite.

The total amount of beryl ore available from the six producing, nonproducing, and undeveloped primary sources in the United States and Brazil is approximately 407,000 mt with an average grade of 10 pct BeO equivalent. Three Brazilian producing districts represent 98.3 pct of the total available beryl ore. Two nonproducing deposits in Brazil and one in the United States represent the remaining 1.7 pct. The U.S. beryl ore deposit is not included on the availability curve because the costs associated with the underground mining and flotation of beryl have no basis of comparison with those of Brazil's surface mining and hand-sorting methods.

The total beryl ore available from Brazilian sources is illustrated in figure 14. Each metric ton of beryl ore contains approximately 10 pct BeO equivalent. The price per metric ton of beryl ore includes the cost of the ore, transportation to major U.S. ports, and insurance costs. Approximately 360,000 mt beryl ore would be available, given a beryl ore price range of $900/mt to $950/mt and a 0-pct DCFROR. The computed prices, which represent the break-even point, for the five Brazilian deposits occur within a range of $900/mt to $1,520/mt beryl ore. Inclusion of a 15-pct rate of return in the discounted cash flow analysis raises the computed price range of beryl ore to $900/mt to $1,555/mt. No change in the $900/mt calculated price has occurred because capital costs for that particular deposit are low.

Sensitivity analyses, in which increments and decrements of 20 pct were affixed individually to transportation costs to Brazil ports, operating costs, and capital costs while the other costs were held constant, disclosed that changes in operating costs had the greatest impact on the

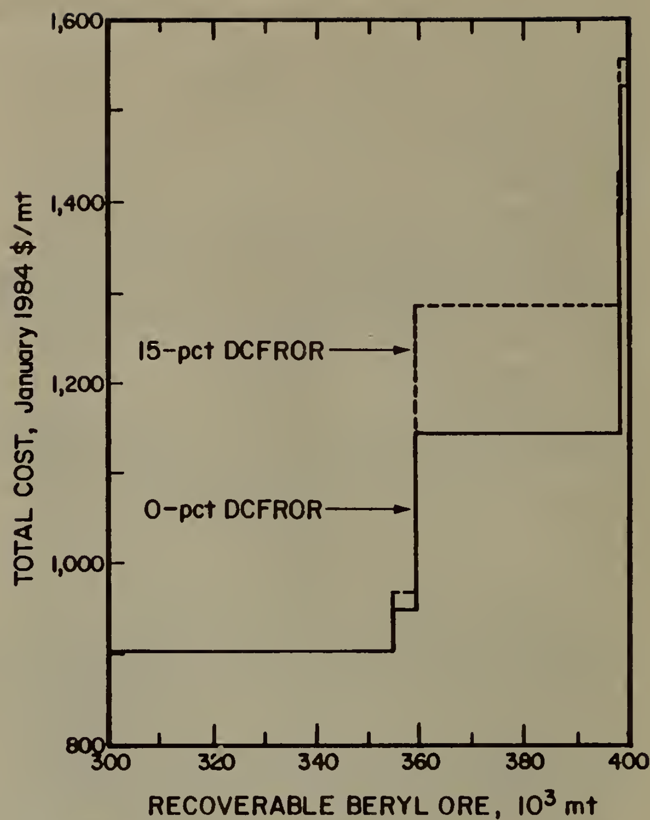


FIGURE 14.—Cost and total availability for Brazilian beryl ore.

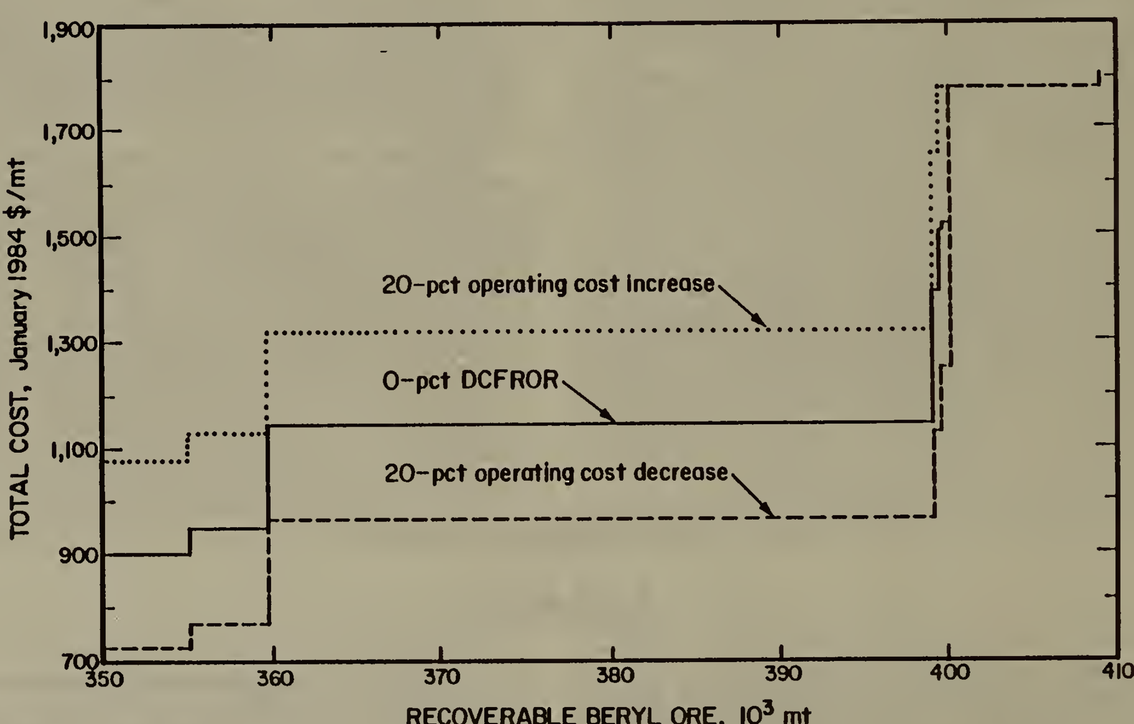


FIGURE 15.—Cost and total availability for Brazilian beryl ore with mine operating cost adjustments.

calculated price of beryl ore owing to the labor-intensive nature of Brazil's beryl ore production. A rate of return of 0 pct and January 1984 U.S. dollars were specified in the sensitivity analyses performed on the Brazilian deposits. A plus or minus change of 20 pct in operating costs caused a 17.1- to 19.5-pct change in the calculated price of beryl ore. The relatively high rate of change in calculated price attributed to change in operating costs graphically confirms the labor-intensive mining technique employed in Brazil (fig. 15). A 20-pct change in transportation costs represented a 0.4- to 0.5-pct change in the calculated price of beryl ore; for capital costs, a 20-pct change represented a 0.0- to 2.3-pct change.

## CONCLUSIONS

Beryllium is available for present and future needs from three ore sources—beryl, bertrandite, and phenacite—with beryl and bertrandite ores being the major sources of beryllium at present. Available beryl and bertrandite ores are sufficient to meet projected demand through the end of the 21st century; however, beryl ore availability in the United States is uniquely tied to Brush Wellman's capacity to beneficiate it. Were Brush Wellman unable to treat the imported beryl ore (because of depletion of ore from exporting countries or other factors), beryllium availability in the United States would be dependent on one source, Brush Wellman's Spor Mountain deposit.

Most of the beryl ore available from the MEC's originates in Brazil. Approximately 90 pct of the total beryl ore resource, which contains 56 pct of total contained beryllium, is in Brazil. Except for small amounts exported to France, Japan, and perhaps a few other industrialized countries, most beryl ore produced in Brazil is shipped to the United States.

The United States consumed approximately 74 pct of the total world beryllium production in 1984. Brush Wellman Inc. operates the only beryllium extraction plant in the United States. Based on the Bureau's understanding of Brush Wellman's Utah facilities, they are in a unique position within the mining community in that they can augment extensive bertrandite reserves with beryl ore and produce an intermediate product, $Be(OH)_2$, or they can produce $Be(OH)_2$ strictly from bertrandite ore.

## REFERENCES


1. U.S. Bureau of Mines and U.S. Geological Survey. Principles of a Resource/Reserve Classification for Minerals. U.S. Geol. Surv. Circ. 831, 1980, 5 pp.
2. Walsh, K. A. Extraction. Ch. in Beryllium Science and Technology, ed. by D. R. Floyd and J. N. Lowe. Plenum, v. 2, 1979, pp. 2–83.
3. Frankeny, J. L., and D. R. Floyd. Ingot-Sheet Beryllium Fabrication, Report of work done under contract between U.S. AEC and Dow Chemical Co., Rocky Flats Div., Feb. 9, 1968, 29 pp.
4. Darwin, G. E., and J. H. Buddery. Beryllium. Academic, 1960, 392 pp.
5. Metals Design. Beryllium. Mar. 19, 1981, pp. 71–72.
6. Engineering and Mining Journal. Various 1984 issues.
7. American Metal Market. Beryllium Prices. v. 93, no. 23, Feb. 4, 1985, p. 28.
8. U.S. Bureau of Mines. Mineral Commodity Summaries, 1976–85. Chapter on Beryllium.
9. Petkof, B. Beryllium. Ch. in Mineral Facts and Problems, 1985 Edition. BuMines B 675, 1985, pp. 75–82.
10. Nininger, R. D. Minerals for Atomic Energy: A Guide to Exploration for Uranium, Thorium and Beryllium. Van Nostrand, 1954, 367 pp.
11. Johnston, W. D. Beryl-Tantalite Pegmatites of Northeastern Brazil. Geol. Soc. America Bull., v. 56, 1945, pp. 1015–1069.
12. De Alameida, S.C., W. D. Johnston, Jr., O. H. Leonardos, and E. P. Scorza. The Beryl-Tantalite-Cassiterite Pegmatites of Paraiba and Rio Grande do Norte, Northeastern Brazil. Econ. Geol., v. 39, 1944, pp. 206–223.
13. Davis, L. J. Beryllium and Uranium Mineralization in the Spor Mountain Area, Juab County, Utah. Paper in Proceedings Basin and Range Symposium, 1979, pp. 397–403; reprint available from Rocky Mountain Association of Geologists and Utah Geological Association, Denver, CO.
14. Brush Wellman, Inc. Annual Report. 1984, 40 pp.
15. Schiller, E. A. Beryllium—Geology, Production and Uses. Min. Mag., v. 151, Apr. 1985, pp. 317–322.
16. Industrial Minerals (London). Beryllium, Thor Lake. No. 204, Sept. 1984, p. 17.
17. Mining Journal (London). Mining Week, Highwood's Rare Metals Bonanza. v. 304, no. 7804, Mar. 15, 1985, p. 171.
18. Berryhill, R. V., and J. T. Mulligan. Beryllium Investigations of the Lost River Mine, Seward Peninsula, Alaska. BuMines OFR 1–65, 1965, 71 pp.
19. Denver Mining Co. Flowsheet Study. Beryl Ore Flotation. Bull. M7–F62, 2 pp.; available upon request from A. A. Soja, Minerals Availability Field Office, BuMines, Denver, CO.
20. Davidoff, R. L. Supply Analysis Model (SAM): A Minerals Availability System Methodology. BuMines IC 8820, 1980, 45 pp.

# APPENDIX A. — U.S. BERYLLIUM DATA

## U.S. BERYLLIUM STOCKPILE

The U.S. strategic minerals stockpile contains beryllium metal ingots of 98-pct-pure beryllium, beryllium-copper master alloy, and beryl ore. The United States began stockpiling beryl ore in 1947 and beryllium-copper master alloy and beryllium ingots in 1965. The stockpile has contained approximately 6,701 mt beryllium-copper master alloy since 1965. The stockpile acquired 139 mt beryllium ingots in 1965; since 1965, the stockpile has gradually acquired ingots to attain the present 236 mt, and 27 mt are now on order. Figure A-1 indicates the amount of beryl ore held in the stockpile from 1950 to the present.

## U.S. ENVIRONMENTAL CONTROLS

In previous years, airborne beryllium particulates were the cause of serious health problems to employees and their family members and to residents of communities near processing sites who were exposed to beryllium dust particles. Berylliosis, a chronic disease, affects the lungs, heart, liver, spleen, and kidneys. Onset of symptoms of the disease may be delayed many years. The occurrence of beryllium-related health problems has diminished since companies involved with the production of beryllium have improved the air quality of the workplace.

The National Emission Standards for Beryllium, under the Code of Federal Regulations, Title 40 CFR 61.30, Subpart C, specify that emissions from individual sources not exceed 10 g Be over a 24-hr period. Sources of beryllium emissions, in addition to extraction plants, include ceramic plants, foundries, incinerators, and propellant plants. Rather than complying with the 10-g limit, an owner or operator may request a variance from the Administrator to average emissions over a 30-day period; in these cases, the concentration limit of beryllium in the vicinity of the source is 0.01 $\mu g/m^3$. A number of conditions must be met to qualify for the Administrator's approval of a variance for an alternate method. Also included in Title 40 are stack sampling procedures outlined under paragraph 61.33 and air sampling procedures outlined under paragraph 61.34.

Beryllium is deposited in oceans and streams through normal weathering processes. Beryllium's natural concentration in sea water is 0.0006 $\mu g/L$. In fresh water, beryllium's toxicity is 100 times greater in soft water than in hard water.

The Environmental Protection Agency (EPA) has included beryllium as a toxic metal pollutant in the NPDES Permit Application Testing Requirements, 40 USC 122.21. NPDES applicants whose processes discharge pollutants are required to report quantitative data for each pollutant listed in appendix D of 40 USC 122.21. A national standard for maximum concentration of beryllium in fresh water has not been established.

The EPA will be issuing new rules regulating beryllium and also will be considering termination of existing exemptions of mine wastes as being considered hazardous substances.

## GOVERNMENT REGULATIONS

In the United States, under Federal Regulation 30 USC 400, provision has been made for operators to obtain Federal assistance for the purpose of exploring for reserves of 27 minerals or mineral products. Beryllium is one of the eligible minerals for which an operator may obtain funding equal to 50 pct of allowable costs of exploration. Analysis of the effects of the regulation on the currently producing property and nonproducing properties did not appear to be warranted in determining the availability of beryllium, since beryllium exploration in recent years has not been extensive.

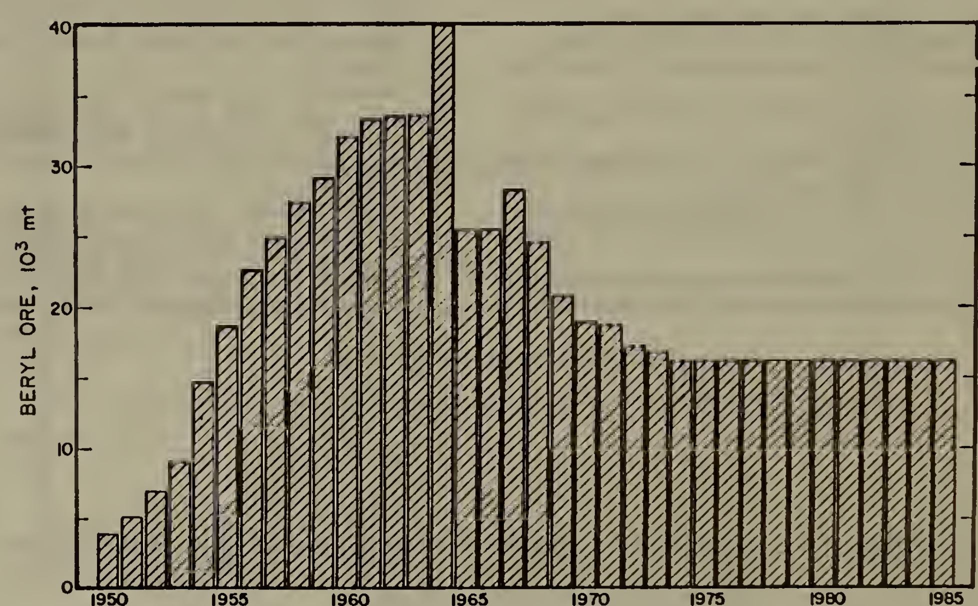


FIGURE A-1.—Beryl ore in U.S. strategic stockpile.

## APPENDIX B. — GLOSSARY

**Beryl.**—A widely mined beryllium mineral; found generally in pegmatites.

**Beryl ore.**—Concentrated beryl; when beryl is mined from a pegmatite, the hand-cleaned and sorted beryl crystals constitute beryl ore; primarily imported into the United States from Brazil, beryl ore contains a minimum of 10 pct BeO.

**Beryllium.**—Be, the fourth element in the Periodic Table.

**Beryllium hydroxide.**—$Be(OH)_2$; this concentrated beryllium material is the end product of Brush Wellman's Delta plant; bertrandite and beryl ore are fed into the plant to produce $Be(OH)_2$.

**Beryllium oxide.**—BeO; the weight percent of this compound in an ore constitutes the ore grade.

**Bertrandite.**—A beryllium silicate mineral generally found in a disseminated form; the only operating bertrandite mine is Brush Wellman's Spor Mountain complex in central Utah.